INFLUENCE OF WIND FREQUENCY ON ROTATIONAL SPEED ADJUSTMENTS OF WINDMILL GENERATORS

Ulrich Hutter

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16. Abstract

In installing groups of windmill generators to produce electric power from the force of the wind, it is important to locate the units of such a network in such fashion that the so-called "two-minute variation" of the wind velocity can be overcome. This is done by using at least three windmill generators located an appropriate distance apart. When the wind velocity is insufficiently great to drive the blades of the windmills, a source of power should be available (battery, power from other windmills) to keep the blades turning. Contrary to popular misconception, changing the angle of attack of the windmill blades does not improve the efficiency of their operation or increase the power of the windmill, as is the case for an aircraft propeller. The reason for this is that the windmill is a passive machine while the aircraft propeller applies energy to the airstream through which it passes.

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INFLUENCE OF WIND FREQUENCY ON ROTATIONAL SPEED ADJUSTMENTS OF WINDMILL GENERATORS

Ulrich Hutter

Aside from purely design-related matters, a consideration /117*
of the economic aspects of windmill generators will reveal that the problem of rotational speed adjustments is a significant one. At first glance it would seem (as suggested by Gaenger [1] among others) that a gear box with continuously adjustable transmission ratio during operation would be necessary between the windmill with its rigid form of drive and the generator. However, following a more careful examination considerations of both the speed/torque curves of the windmill and the generator and the statistical frequency values for the wind velocity reveal that it is at least questionable whether the unavoidable matching losses with a fixed transmissionratio could actually be avoided by installing a drive with a continuously variable transmission ratio; on the whole, the relatively high internal losses of such a drive would occur at all operating ranges, while the matching losses of a rigid drive could be eliminated by appropriate selection of the transmission ratio under operating conditions that would be most profitable as far as energy output is concerned. The increased cost of the installation resulting from such an intermediate drive has the same effect in the final analysis on the cost of energy production as a further loss would have.

Economic Value

The feasibility of windmill generators and their competitive position with respect to water powered and thermal generators isgoverned by the price of a kilowatt hour. The latter is obtained from the quotient of the total expenditure (for design, manufacture, installation, maintenance, service, repairs, capital

*Numbers in the right-hand margin indicate pagination in the foreign text.

investments, land costs, etc.) and the total energy produced (in the course of the period covered by the lifetime of the installation), multiplied by the utilization factor n (see Huette, Volume 2, page 571):

$$p\,[\text{pfennigs/kWh}] = \frac{100 \cdot \sum K(\text{DM}) \cdot n}{T_L(\text{years}) E(\text{kWh/year})}. \qquad (1)$$

In the event of mass production of medium sized installations, the manufacturing cost alone could run far above all other expenses, so that if we disregard the operating time, which has a rather considerable influence on the price of the electricity, but which we shall deliberately not discuss here, the lifetime, manufacturing cost and annual energy output remain as the most important parameters effecting the economic factor.

The lifetime of windmill generators can be raised to an acceptable level by using the means which govern the lifetime of the high voltage masts, crane installations, generator drives and generators and which are basically known without the difficulties which are rather typical of windmill generators.

The manufacturing cost is determined by the type of construction. It may be kept small by using structurally simple solutions, employing in part structural elements which have been manufactured for years in large quantities, and by limiting the project to installations of a size which lends itself to mass production. In addition to the lower distribution costs of the electricity produced, the improved internal load distribution when several generators are working together, the reduced danger posed to the air space by air navigation hazards that are difficult to recognize, the smaller development risk, the faster realization of large improvements in the energy economy, etc. are the most important arguments for installations with rather moderate dimensions and against Utiopian giant projects which are unable to utilize the principal advantage of windmill generators, namely, to be independent of their location to a certain degree. In particular, no structural complications can be taken into account before a careful examination of the entire economic situation has shown that something will in fact be gained by such a project. It is necessary, however, that all of the factors involved in actual operation be taken into account.

The annual energy output is determined by the local wind conditions, the size of the installation and the degree of utilization ε_a based on the total energy output. Similar wind conditions are repeated constantly in an annual rhythm. The deviation from the average energy output in subsequent years amount to a maximum of $\pm$ 5 to 7% according to Bielau [2].

As far as the design problems which crop up when optimum solutions are being sought are concerned, only one question will be discussed here: What method of changing the ratio between the large windmill, turning very slowly at a high specific rate

$$\lambda = \frac{\text{velocity of blade tips}}{\text{wind velocity}}$$

and the generator will give the best economic factor, in other words, the lowest price for the electricity produced (for example, the rotational speed for $\lambda = 8$ at a wind velocity of 7 meters per second and a windmill diameter of 40 meters is only small and equals 27 rpm).

It should also be pointed out that for this size wheel it is not immaterial what the size ratio between the generator and the drive is. As an extreme, one can mention the solution proposed by Honnef [3] for a drive-less installation with a specially built giant ring generator (What would be the accuracy of the installation? How large would the air gap have to be? How would the question of icing be dealt with?), or on the other hand, a design with a drive having a large number of steps and an extremely high transmission ratio (Would it be self-locking?) and a small generator turning at a very high speed. Aside from very small installations in which no gear box is required, the optimum generalized somewhere

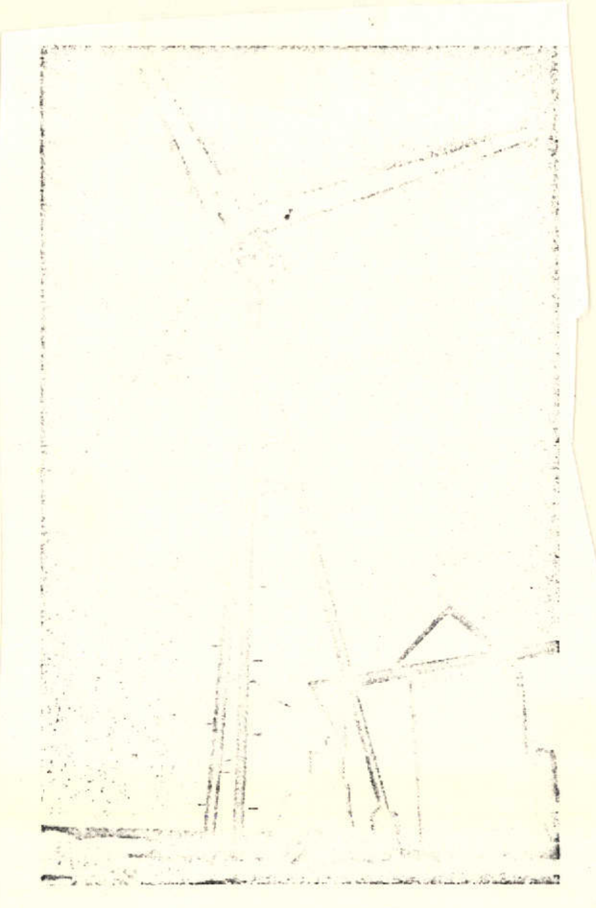

Figure 1. Windmill generator designed by the author. Wheel diameter 8 meters, speed λ = 8. Installed power (depending on wind frequency at the site) 2 kilowatts to 5 kilowatts. Energy output 7,000 to 12,000 kW/h/year.

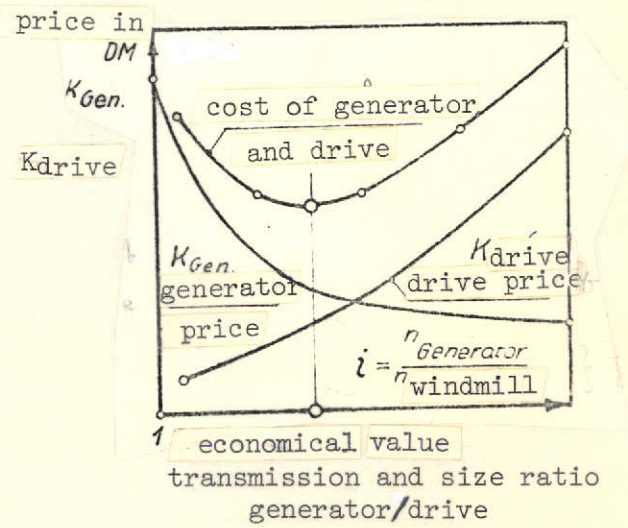

Figure 2. Generator and drive costs versus transmission ratio between generator and windmill (purely qualitative representation of the relationship).

between these two extremes. Several parallel designs have made it clear relatively rapidly what size ratio between the generator and the drive provides the minimum expenditure (Figure 2).

The Problem of Constructing a Network

The behavior of the generator depends onwhether the installation is intended to operate in a network or independently of a network. The least satisfactory case for matching is when the generator is a synchronous machine controlled by a powerful network. The conditions do not change significantly if an asynchronous machine is used instead of a synchronous machine. The flight slip does not lead to any noticeable improvement in matching. The situation is slightly different when compound direct current machines are used for which a certain matching to optimum windmill power curves is possible within narrow limits by appropriate installation, but apply only to small and very small installations and are therefore only of minor interest here.

Power supply and consumption from a network that balances /119
its reserves is necessary for all windmill generators which must be used for a steady supply of current and for which no interruption due to insufficient energy is permitted. In densely populated areas where there is a network powered by large water-powered or thermal power plants, the windmill generator is connected to the network, pumps the excess energy into the network and draws the necessary energy from the network when its own output is inadequate.

In sparsely populated areas, an energy storage device with a sufficiently large capacity must make up the deficit. The installed power of the storage device is therefore generally much larger than that of the windmill generator. If the amount of energy supplied by the windmill generator is insufficient, the storage device will work together with the windmill generator and drive the latter. If the energy output from the windmill generator exceeds the demand, the blades can be adjusted so that the rotational speed and frequency will remain constant. In addition, several (at least 3) windmill generators connected together can achieve a certain balance that may be particularly advantageous for all residential and industrial installations. This has the advantage that the brief wind shifts which are most frequent and have the most disturbing effect with regard to uniform operation, produced by cyclic air movements near the ground, i.e., by ground turbulence, can be eliminated with a high degree of probability without having to rely on a storage device (storage losses are eliminated). Almost all wind measurements reveal a typical "2-minute variation" in wind velocity which amounts to $\pm 20\%$ to $\pm 60\%$ of the mean wind velocity depending on local conditions; this corresonds to a constant power variation of $\frac{+75\%}{-50\%}$ to $\frac{+300\%}{-93\%}$ (Figure 3). This brief variation, whose frequency increases with wind velocity, corresponds toan average "wind wavelength" of 500-600 meters at velocities up to 8 meters per second. Installations connected together must therefore be approximately 300 meters apart so that the maximum probability of compensating for the instantaneous variations can be achieved in the most frequent operating ranges.

A fitting task for statistics would be to determine the most favorable number of windmill generators working on a common ring connection and their most favorable mutual positions on the basis of available measurements of the instantaneous wind velocity.

Operation without a network and without a storage device to provide current produces no difficulties in adjustment of the type described here. It is involved when the user himself can store the energy produced by simple means and is not forced to turn it back into electrical energy. This is the case for all water pumping works for all operations that use heat alone such as wood and fruit drying facilities, simple room heating and hot water production, as well as brickworks, distilleries, etc., as well as certain sections of chemical industries (distillation, electroylis, and so on). In the case of such consumers the adjustment depends on the load. By means of a constant adjustment as a function of wind velocity, the active load is kept high enough so that the torque and speed are always such that the optimum value for energy conversion is attained at the prevailing wind velocity by the windmill (C_{Lopt}).

Hence, in all of the cases of interest to us here, we are dealing only with generators having very steep curves (dM/dn very large or equal to ∞) and therefore will deal in the following only with the "least satisfactory" case of the network-controlled synchronous machine (fixed rotational speed).

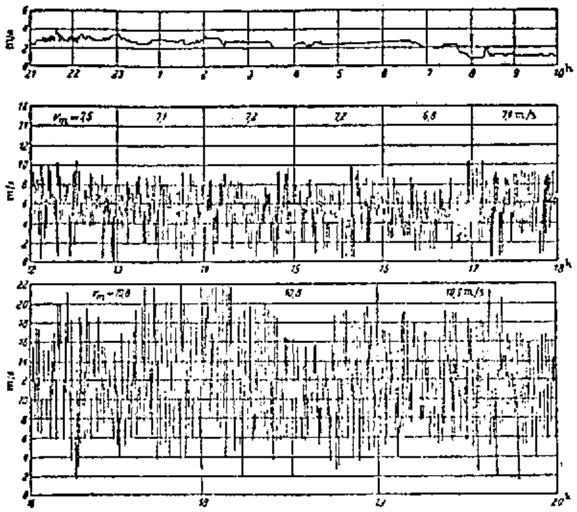

Figure 3. Wind velocity as a function of time at low, medium and high wind velocity. Recorded at Potsdam with a gust recorder [20].

Behavior of the Windmill.

The instantaneous equilibrium condition for the generator shaft in stationary operation requires that

$$i \cdot M_{generator} = M_{windmill} \cdot \eta_{drive}. \quad (2)$$

Here $i = \frac{n_{Gen}}{n_{Wheel}}$ is the transmission ratio and η_{drive} is the efficiency of the drive. If a continuously adjustable hydraulic or friction wheel drive is installed, the drive slippage causes an additional loss in both i and η_{drive}. The torque produced by the windmill is a function of the rotational speed n_W of the wheel (R.P.M.), the wind velocity (in the range no longer influenced by the wheel), v_0 (meters times seconds^{-1}), the air density ρ (kilograms sec^2 meter^{-4}) and the angle of attack of the blades β_0. This is the angle which some defined reference line--for example, the geometric chord or the direction of zero incidence--of a certain blade profile (usually at 72% of the blade tip radius) forms with the plane of rotation of the wheel (Figure 4). /120

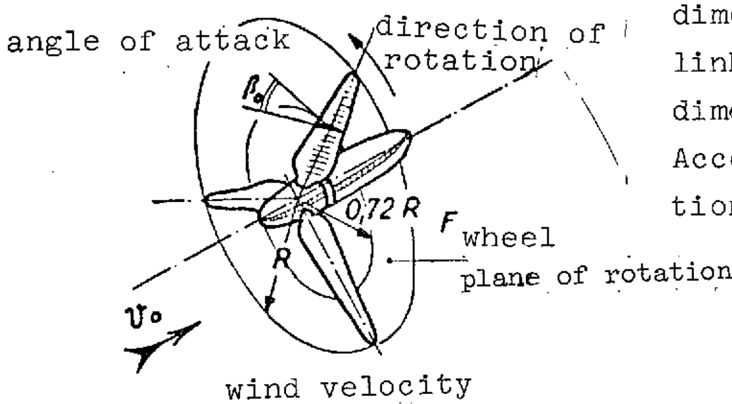

Figure 4. Plane of rotation of the wheel and angle of attack of the windmill blades.

The torque, speed and applied power of the wheel are given by dimensionless parameters which link these values to the wheel dimensions and the wind velocity. According to conventional definitions,

$$M_W = c_d \cdot v_0^2 \cdot R \cdot F_W \cdot \frac{\rho}{2} \text{ [kgm]}; \quad (3)$$

$$n_W = \lambda \cdot \frac{v_0}{R} \cdot \frac{30}{\pi} \text{ [U/rpm]}; \quad (4)$$

$$L = c_L \cdot v_0^3 \cdot F_W \cdot \frac{\rho}{204} \text{ [kW]}. \quad (5)$$

In the above, R is the blade tip radius (m) and F_w is the area of the circle described by the wheel, equal to $R^2\pi(m^2)$ (See Figure 3), c_d is the dimensionless moment coefficient, λ is the speed $\frac{R\omega}{v_0}$ and c_p the power coefficient. c_p is a type of efficiency. However, because the ideal best value for c_p is only 0.593, it is not called efficiency although it is a measure of the value of a windmill with reference to the utilization of the energy of the wind. From equations (3) to (5), we obtain the following simple realtionship between c_p, c_d and λ:

$$c_d = \frac{c_p}{\lambda} \tag{6}$$

It is therefore only necessary to know two of the three dimensionless parameters in order to be able to determine the behavior of the wheel in advance. In most publications on the results of wind tunnel measurements of windmill models, both c_p and c_d are given for one or more angles of attack β over λ (Figures 5 to 7).

According to equation (6), c_d is the tangent of the angle φ (Figure 5) which the radius vector at a certain point on a c_p-λ curve forms with the abscissa. From the shape of the c_p-λ curves one can see that with increasing λ the maximum value of $c_d = \tan\varphi$ is reached before the best value of c_p. This can be seen clearly by comparing Figures 5 and 6 and from Figure 7 as well. As λ increases further (with v_0 = const, in other words with increasing rotational speed) c_d decreases and hence the torque drops steadily to zero (Figure 6). The most favorable operating points of the wheel therefore lie in every case in an area of decreasing torque as the rotational speed increases. All points of intersection of the torque/speed lines of the wheel with the steep torque/speed curves of the generator are therefore stable operating points and not only statically but also dynamically, as Professor Kloss [4, 5] have shown.

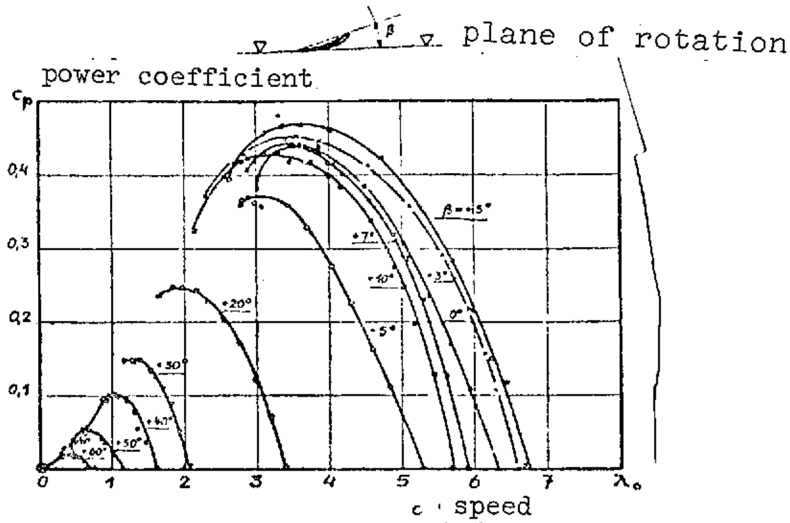

Figure 5. Power coefficient versus speed for eleven different blade angles of attack measured on a 4-bladed windmill model designed by the author, with a diameter of 1.36 m, in the wind tunnel of FKFS Stuttgart-Unterturkheim. April 1942 [12].

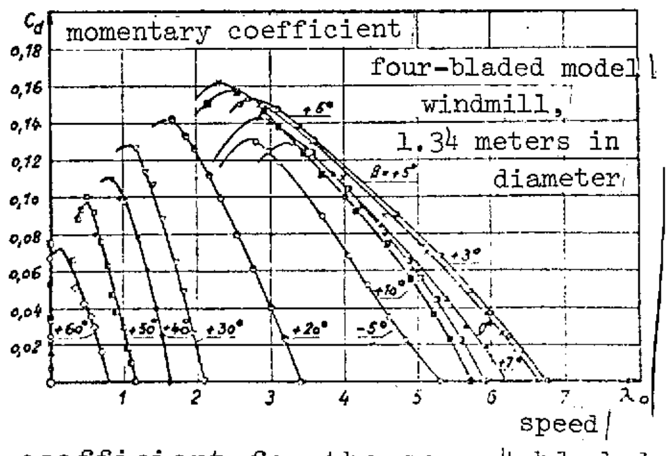

Figure 6. Torque coefficient for the same 4-bladed windmill model [12].

There is another important fact that can be seen from Figures 5 and 7: The c_p-λ curve which reaches the highest c_p value also nearly encloses all others in the range which is of importance to operation ($\beta_0 = +5°$ in Figure 5, $\beta_0 = +4°$ in Figure 7). Measurement results obtained with wheels at different speeds and numbers of blades show quite similar results. This means that in the case of windmills, in contrast to airscrews, the rotational speed can not be increased at all by feathering the blades if the wind velocity is too low. This fact becomes particulary clear if we plot the optimum c_p value and the maximum possible λ value (the rotational speed that will fracture the blades, λ_{max} at $c_p = 0$) against the angle of attack of the blades (Figure 8). Both values have a very sharp peak at a quite specific blade angle. By way of comparison, Figure 9 shows the range of efficiency of an adjustable propeller (airscrew) [6]. The propeller modulus λ plotted on the abscissa is the reciprocal of the speed R/v_0 which is also referred to as λ in windmills. In the case of the propeller, by adjusting the angle of attack of the blades the propeller modulus can be set to the optimum efficiency as a function of flight speed and a gain in power can be achieved. In the case of windmills on the other hand, adjusting the blades can only eliminate the often considerable power excesses. In the most important operating range, however, from 0 power to full load, the range which the installation is subject to for 70-85% of its operating time depending on the installation and the local wind conditions, blade adjustment makes no sense. These basically different modes of behavior of the airscrew and the windmill are due to the fact that the airscrew is an active machine which transfers the energy in its shaft to the air stream, while the windmill passively achieves the specific maximum value of energy conversion from a given air flow only when a certain optimum setting is achieved.

The blade adjustment is therefore not a way of achieving improved rotational speed adjustment in windmill generators, or of attaining an improved energy yield, as is frequently assumed falsely to be self evident, but merely a way of satisfying the following conditions:

1. In the case of very high speed units (λ = 8 to 16), which are used only for medium and large wind generators, to facilitate starting (the momentary coefficient c_{d0} at $\lambda = 0$ increases perceptibly with β . Application of previously extracted flow;

2. Preventing the overspeeding of the installation by operating without a load (Figure 8); /122

3. At high and very high wind velocities, keeping the torque and speed within the limits set by the installed maximum load;

4. Always being able to stop the installation within a few seconds without developing large dangerous gyroscopic couples;

5. In the case of wheels of very large size, by means of constant monitoring of each individual blade, to be able to balance out the large anticipated aerodynamic static imbalances and those caused by the different positions of the blades with respect to the plane of rotation. These imbalances have been one of the most important problems that had to be overcome in large helicopters [7]. In the case of very large wheels, they produce very uneven velocities, as one would expect for such large areas.

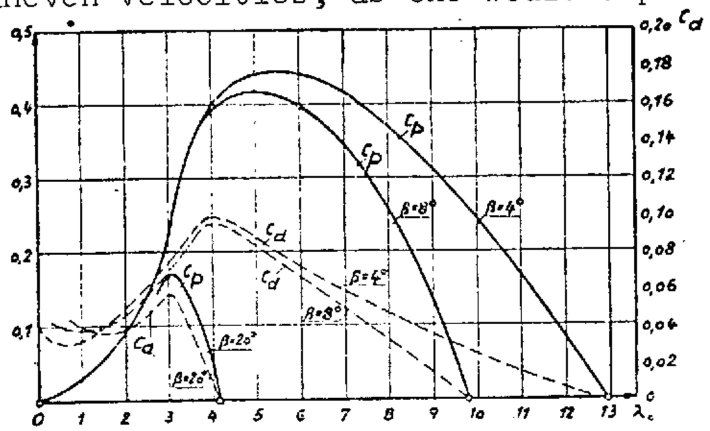

Figure 7. Power and momentary coefficient versus speed. Measured by Caille Ackerett, Zurich Institute of Technology [10].

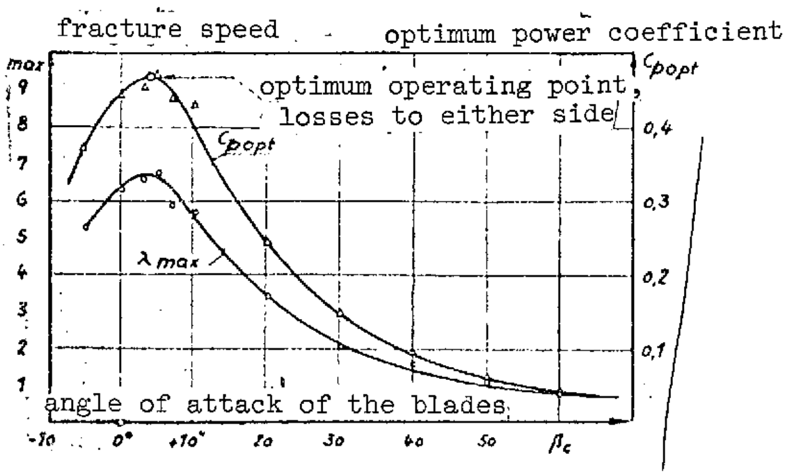

Figure 8. Maximum attainable speed λ_{max} at $c_p = 0$ and the optimum value of c_p, $c_{p\ opt}$ plotted as a function of angle of attack of the blades β_0. The two curves are an evaluation of Figure 5. a--fracture speed; b--optimum power coefficient; c--optimum operating point, losses to either side; d--angle of attack of the blades.

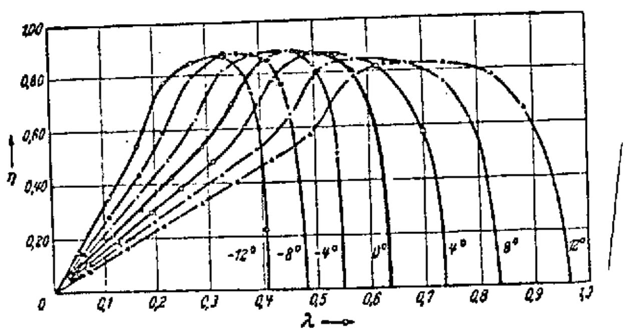

Figure 9. Efficiency of an airscrew as a function of propeller modulus $\lambda = \frac{v}{u}$ with angle of attack of the blades as a parameter [6].

The above listed facts simplify the practical calculation of the matching problem; instead of having to plot the speed/torque curve families for several blade positions, obtained by using wind velocity as a paramter, it will suffice to calculate the graph with the c_p-λ curve, which gives the best c_p values (Figure 10).

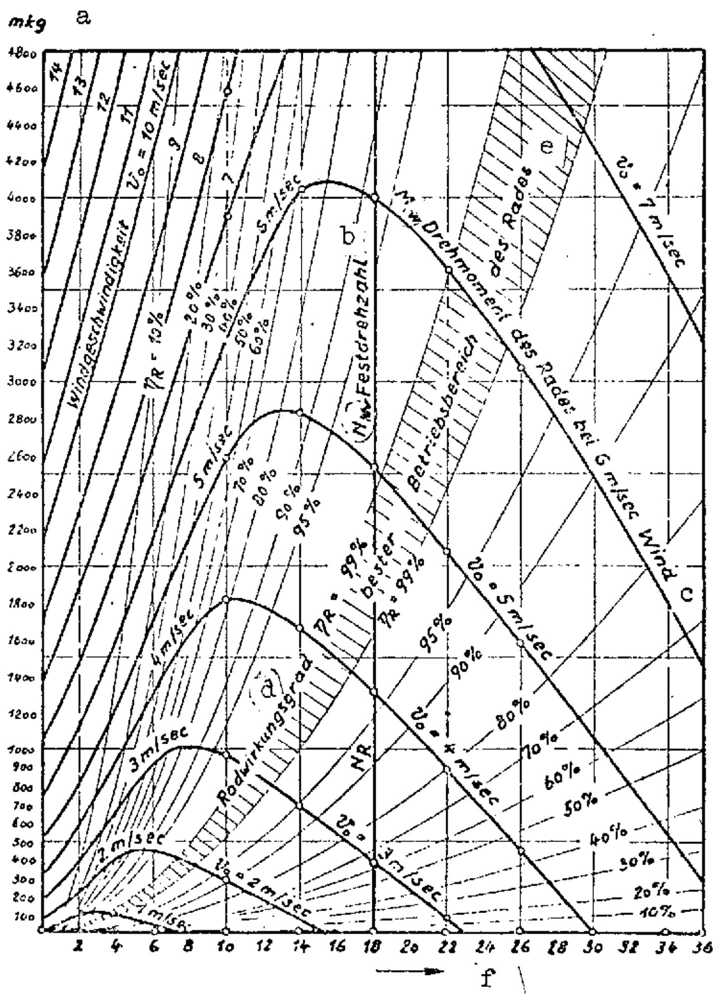

Figure 10. Torque-speed curves of a windmill with a diameter 40 m and a drive speed $\lambda = 8$ with the wind velocity as a parameter. The family of η_W = const curves characterizes the area of equal degree of efficiency of the wheel. a--M_W wheel torque; b--N_W sixth rotational speed; c--M_W torque of wheel at 6 m/sec wind; d--wheel efficiency η_W = 99%; e--optimum operating range of wheel; f--R.P.M. rotational speed of wheel.

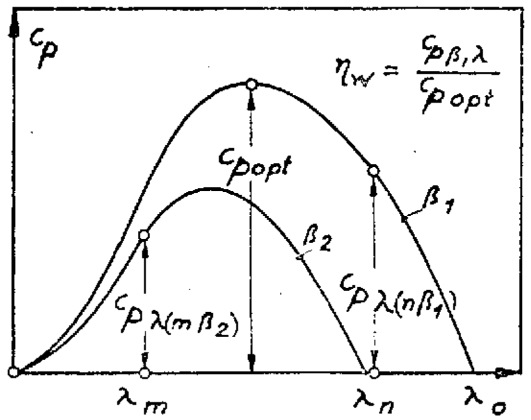

Figure 11. Definition of wheel efficiency η_w for two c_p curves of different blade angles of attack.

It has already been pointed out repeatedly (most clearly by Professor Kloss) that it is misleading to state that the speed increases proportionately to the wind velocity, the torque with the square and the power with the cube of the wind velocity. This is true, if we look at equations (3), (4) and (5), only for firmly established λ, c_d and c_p values, in other words for one point on the curve of the c_d-λ curves. On the other hand, if the rotational speed n_w is kept constant with varying wind velocity, the wheel will turn at a different speed at each velocity. However, because the best possible value of c_p can be achieved only for a certain value of λ_{opt} in all other cases the possible power optimum is not utilized completely. If we use

$$\eta_w = \frac{c_{p\lambda,\beta}}{c_{popt}} \tag{7}$$

as the wheel efficiency the ratio of the actual possible power coefficient set by the conditions determined by the generator and the wind to the best possible value (Figure 11) and plot the curves of equal η_w values in the torque/speed diagram, one can immediately get an idea of the losses for each generator characteristic (calculated for the wheel torque) which actually results when the rotational speed is fixed (Figure 10).

[to be continued].